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TECHNICAL NOTE

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EMPIRICAL METHOD FOR FREQUENCY COMPENSATION

OF THE HOT-WIRE ANEMOMETER

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SUMMARY

Improvements in the design of equipment associated with the hot-wire anemometer for the measurement of fluctuating air-flow quantities are described. An improved technique and an electronic circuit for the frequency compensation of a hot wire are presented. Use of the electronic circuit permits rapid empirical determination of the frequency-response characteristic of a hot wire under actual wind-tunnel operating conditions. A frequency-compensation circuit is provided, the frequency-response characteristic of which may be continuously varied to match wind-tunnel operating conditions throughout the design frequency range of the instrument (10 to 1000 cps). Experimental verification of the theory involved and of the frequency-compensation circuit developed is included. The methods developed are not limited to the specific frequencies and mass-flow measurements considered but are applicable to all dynamic measurements with a hot wire in which the flow variations are small with respect to the mean flow.

INTRODUCTION

The measurement of dynamic-air-flow phenomena in wind tunnels is becoming increasingly important. The hot-wire anemometer is well adapted to measurements of this type because of the high sensitivity, small size, known theoretical frequency response, and simple construction. The known theoretical frequency-response characteristic of a hot wire makes it particularly applicable to the instantaneous observation of rapidly varying flow quantities.

The main disadvantages in using the hot-wire anemometer are the nonuniform response characteristics of the wire and the fact that the corrections to be made for compressibility effects are unknown. The dynamic-response of a hot wire is such that the amplitude of electrical output signal produced by a constant-amplitude flow variation decreases as the frequency of the flow

variation increases (reference 1). A number of circuits compensating for this effect have been developed but none of these has proved completely satisfactory except under specific isolated operating conditions.

The work herein discussed was undertaken in an effort to overcome the disadvantages of previous methods for determining the frequency-response characteristic of a hot wire and for effecting a compensation for this response. (See, for example, reference 2.) It was also desired to extend the useful range of the hot wire to high airspeeds for which the potential-flow conditions assumed in the classical hot-wire theory no longer apply.

THEORY OF THE HOT-WIRE ANEMOMETER

The steady-state theory of the hot-wire anemometer is based upon King's equation for the heat loss from a small heated cylinder in a moving air stream. (See reference 3.) King's equation relates heat loss, cylinder temperature, and air-flow conditions as follows:

$$\frac{dH}{dt} = \left(K + C\sqrt{\rho V}\right)\left(T - T_0\right) \tag{1}$$

where

H   heat energy per unit length of cylinder, watt seconds per centimeter

ρ air density, grams per cubic centimeter

V   air velocity, centimeters per second

T   cylinder temperatures, $^{\circ}$C

T_0 free-stream temperature, $^{\circ}$C

t   time, seconds

C, K   constants

Equation (1) is based on the assumption of nonviscous incompressible flow conditions. The air velocity V is also assumed large compared with the free convection velocities which would normally exist about the wire. Under steady-flow conditions the quantity dH/dt is equal to the electrical power supplied to the wire.

A differential equation for the dynamic response of a hot-wire anemometer when operated with constant current has been derived in reference 1 as follows:

$$\frac{dH}{dt} = 4.2\sigma A^2 s \frac{dT}{dt} \qquad (2)$$

where

σ density of wire, grams per cubic centimeter

A cross-sectional area of wire, square centimeters

s specific heat of wire, calories per gram per $^\circ C$

Equation (2) is the time derivative of the familiar relationship among heat, thermal capacity, and temperature. Algebraic manipulation of the relationships among temperature, resistance, and the temperature coefficient of resistance yields

$$T - T_0 = \frac{R - R_0}{R_0 \alpha} \qquad (3)$$

where

α temperature coefficient of resistance, ohms per ohm per $^\circ C$

R wire resistance per unit length at temperature T, ohms per centimeter

R_0 wire resistance per unit length at temperature T_0, ohms per centimeter

From equation (3)

$$\frac{dT}{dt} = \frac{1}{R_0 \alpha} \frac{dR}{dt} \qquad (4)$$

Since the change in heat content of the wire given by equation (2) must be equal to the difference between the power supplied $i^2 R$ and the forced convection loss given by equation (1), the following equation results if the right-hand side of equation (3) is substituted for the quantity $T - T_0$ and the right-hand side of equation (4) is substituted for dT/dt in the combination of equation (1), equation (2), and $i^2 R$:

$$\frac{4.2\sigma A^2 s}{R_0 \alpha} \frac{dR}{dt} = i^2 R - \left(K + C\sqrt{\rho V}\right)\left(\frac{R - R_0}{R_0 \alpha}\right) \qquad (5)$$

where

i   wire supply current, amperes

The constant-velocity condition is obtained by letting $\frac{dR}{dt} = 0$ in equation (5); thus

$$i^2 R_e - \left(K + C\sqrt{\rho V}\right)\left(\frac{R_e - R_0}{R_0 \alpha}\right) = 0 \qquad (6)$$

where

R_e equilibrium value of R, ohms

The value R_e is the value of the wire resistance if $\frac{d(\rho V)}{dt} = 0$. If the quantity $K + C\sqrt{\rho V}$ is eliminated between equation (5) and equation (6), the result is

$$\frac{4.2\sigma A^2 s}{R_0 \alpha} \frac{dR}{dt} = \frac{i^2 R_0 \left(R_e - R\right)}{R_e - R_0} \qquad (7)$$

In equation (7) the flow quantities ρ and V have been eliminated and replaced by the forcing function R_e which varies with ρV in accordance with equation (6).

A solution of equation (7) is obtained by assuming a sinusoidal variation of R and solving for the required form of the variation of the equilibrium value R_e. For small variations in R_e the solution obtained shows that the amplitudes of fluctuation of R and R_e are related by the equation (reference 1)

$$\frac{\Delta R}{\Delta R_e} = \frac{1}{1 + j\omega M} \qquad (8)$$

where

ω frequency, radians per second

M   time constant, seconds

Equation (8) includes the phase and amplitude variations introduced. The quantity M is the sole parameter necessary to determine completely the shape of the dynamic-response curve of the wire. The parameter M is related to the physical constants of the wire and the tunnel operating conditions by the following equation:

$$M = \frac{4.2\sigma A^2 s \left(T - T_0\right)}{i^2 R_0} \tag{9}$$

The presence of T, T_0, and R_0 in equation (9) demonstrates M to be a function of the tunnel operating conditions as well as of the physical characteristics of the wire. This consideration is important because tunnel operating conditions cannot always be accurately nor conveniently evaluated.

THEORY AND LIMITATIONS OF CONSTANT-CURRENT

DYNAMIC HOT-WIRE SYSTEMS

Various methods have previously been devised for determining the frequency-response characteristic of any given hot wire and for compensating for this characteristic.

Methods for Determination of the Frequency

Response of the Hot Wire

The dynamic response of a hot wire has been experimentally determined by mechanical oscillation of the wire in a moving air stream. The experimental results obtained are in close agreement with the response predicted by the theoretical work given in reference 1. Inherent mechanical difficulties have limited the applicability of this mechanical-oscillation method to frequencies not exceeding 60 cycles per second.

In reference 4 a synthetic calibration technique for the extension of this frequency range is developed. Refinements of this technique given in reference 2 resulted in experimental verification of the theory throughout the audio-frequency range. The synthetic technique depends upon the similarity of the heat transfer from a wire heated by a small alternating current superposed on the direct heating current to the heat transfer in response to air-flow fluctuations of the same frequency.

In order to permit compensation for the wire frequency response
the time constant must be determined. In both experimental methods
(alternating-current superposition and mechanical oscillation) the
frequency-response curve is determined, and from this determination
a graphical evaluation of the time constant is made. The time
constant may also be determined from equation (9).

The use of equation (9) to determine the time constant requires
that the tunnel operating conditions as well as the physical charac-
teristics of the wire be known. The difficulty of accurately
evaluating the quantities in equation (9) which depend upon tunnel
operating conditions and the quantities determined by the physical
properties of a wire of extremely small diameter makes the accuracy
of the computed time constant uncertain.

Methods of Frequency Compensation of a Hot Wire

Numerous methods have been devised for compensating for the
amplitude reduction factor expressed by equation (8). This com-
pensation may be made for periodically varying fluctuations by
employing the method of Fourier analysis and applying a correction
factor to each frequency component present. Because of the
complexity of this method and the fact that this method is not
applicable if the fluctuations are aperiodic, this dynamic reduction
factor must be compensated for before the signal is applied to the
recorder. Compensation is made by the introduction of a frequency-
compensating network.

In earlier work a value of M computed from equation (9) was
used to determine the frequency characteristic required of the
compensating circuit to effect a composite frequency-response curve
which is uniform throughout the desired range. (See, for example,
reference 2.)

The electrical circuits designed to have a frequency response
reciprocal to that of the wire have been of two general types: a
resistance-inductance network and a resistance-capacitance network.
A method of compensating for the frequency characteristic of the
wire which makes use of a series resistance-inductance combination
is given in reference 1. Although such a system can be made to
satisfy the requirements exactly on a theoretical basis, there are
practical considerations which limit the applicability to a
restricted range of time constant. The utility of the resistance-
inductance type of compensation circuit is limited by the difficulty
of constructing inductance coils with ratios of inductance to
resistance which produce values of the time constants throughout
the range likely to be required. In order to produce large time

constants physically large iron-core inductance coils are required. These large coils are objectionable because their inductance is dependent upon frequency, the associated stray capacity makes a prediction of the circuit characteristics uncertain, and the coils are subject to the influence of stray magnetic fields.

Another method, first proposed in reference 4, for the compensation of the frequency characteristic of a hot wire makes use of a resistance-capacitance combination to yield an approximately correct frequency-response characteristic. This method has a disadvantage in that it requires both a resistance and a capacitance value to be changed simultaneously when the value of M is to be varied. A system which depends on the simultaneous variation of resistance and capacitance possesses the disadvantage of requiring a specially constructed ganged resistance-capacitance combination and is usually practicable only with fixed condensers, the use of which results in a step variation in the time constant rather than the more desirable continuous variation.

EMPIRICAL FREQUENCY COMPENSATION OF A

CONSTANT-CURRENT HOT-WIRE SYSTEM

The need for an empirical method of determining the time constant of a hot wire is apparent when the analysis of the dynamic conditions is extended to permit measurements to be made under compressible-flow conditions. The use of an empirical method for determining this constant has the additional advantages of greater ease of operation and increased dependability of results since the time constant is measured under the actual tunnel operating conditions.

The hot-wire theory of reference 3 is based upon the assumption of incompressible-flow conditions. The derivation of equation (7) shows that the quantity $K + C\sqrt{\rho V}$ taken from equation (1) has been eliminated between equations (5) and (6), which indicates that the ratio of the dynamic response to the static response of the wire to variations in the rate of heat transfer is independent of the relationship between rate of heat transfer and steady-state mass flow. The elimination of the quantity $K + C\sqrt{\rho V}$ from equation (7) is of fundamental importance since it permits the extension of hot-wire dynamic measurements into the range of compressible flow.

To compute the value of the time constant M from equation (9) in the compressible-flow range of velocities is impossible, however, because the air temperature in the vicinity of the wire under these

conditions may differ considerably from the free-stream temperature.
The temperature of the air adjacent to the wire which determines the
response characteristics of the wire will have an effective value
between the free-stream and the stagnation temperatures. This fact
makes necessary empirical determination of the time constant under
actual tunnel operating conditions.

An experimental verification of the applicability of the ampli-
tude reduction equation (8) to hot-wire measurements under compressible-
flow conditions has been made. The method used was a modification of
the methods of references 2 and 4. In this modified method an
alternating current of any desired frequency is superposed on the
direct current heating the wire. The fluctuation in heat supplied
to the wire produces a resistance variation analogous to that resulting
from a fluctuation in mass flow.

The method of operation and general analysis of this type of
circuit has been discussed in reference 2. The greatest difference
between the circuit analyzed in reference 2 and the one shown in
figure 1 lies in the method of introduction of the alternating
component of current into the bridge system. In the circuit shown
in figure 1 the alternating component is introduced through a
transformer. The transformer power rating is such that the direct-
current component in its secondary produces a negligible distortion
of the alternating-current component. This circuit configuration
was chosen rather than the capacity coupling used in reference 2 so
as to minimize losses inherent in capacity coupling at low frequencies.

The circuit and component values shown in figure 1 produce an
essentially constant direct-current system for small variations in
wire resistance. Small deviations from the constant direct-current
condition are unimportant since they are present during both the
static-wire calibration and the synthetic dynamic-response
determination.

When the frequency response of a hot wire is experimentally
determined, the bridge unbalance resulting from an injected carrier
of constant amplitude but variable frequency is proportional to the
response of the hot wire to the signal frequency (reference 2).

In order to insure that the bridge signal output was the result
of changes in wire resistance and was not due to an alternating-
current unbalance in the bridge itself, the hot wire in the bridge
circuit was replaced by a resistor of which the value was independent
of the small changes in current through it and the bridge balance
was checked throughout the audio-frequency range. The alternating-
current bridge null was found to be independent of frequency
throughout this range. With the alternating-current balance of

the bridge established, the voltage appearing across the bridge output terminals with the hot wire in the circuit is a function only of the changes in wire resistance with change in heating current.

The experimentally determined frequency-response characteristic of a wire operating under compressible-flow conditions obtained by the preceding method is shown in figure 2. The particular value of the time constant M which characterizes this curve has been determined graphically and the theoretical response for a wire having the same time constant is shown for purposes of comparison. The experimental curve is seen to be of the same general form theoretically predicted by the time-constant relation derived in reference 1. The agreement is within the limits of experimental error throughtout the frequency range.

In order to compensate for the dynamic error represented by the amplitude reduction equation (8) and illustrated in figure 2, the output signal of the bridge must be supplied to the recorder through a network which has a response that is the reciprocal of

the factor $\dfrac{1}{1 + j\omega M}$. Since the time constant M of the hot wire

depends upon operating conditions, the value of M of the reciprocal circuit must be continuously adjustable to adapt the system to tunnel conditions.

In order to permit an exact determination of the time constant M when the factors entering into equation (9) are not accurately known, the time constant must be determined empirically because the physical properties of the wire material may be considerably altered when the wire is drawn to small diameters. A further limitation to an accurate evaluation of M from equation (9) is the uncertainty regarding the value of the effective free-stream temperature.

The fact that the hot-wire response curve is completely determined by two parameters, the time constant and the static sensitivity, suggests that the value of these parameters may be determined from the absolute response of the wire at any two signal frequencies. The value of M alone may be determined from the relative response at any two frequencies by eliminating the static sensitivity between the equations for the two frequencies.

In practice, the system shown as a block diagram in figure 3 is used for determining the time constant M under the actual operating conditions and for effecting a uniform frequency-response characteristic. With this system, two signals of equal amplitude but of different frequencies are injected simultaneously into the bridge discussed herein. The bridge unbalance voltage is then

amplified by a conventional audio-amplifier, and this signal is
supplied to the compensator. The compensator has a response which
is the reciprocal of the amplitude reduction equation (8). After
the compensator are two amplifiers tuned to the injected signal
frequencies and a meter indicating the difference between their
output signals. In order to set the correct value of M in the
compensator, the setting of the time-constant control is varied
until the response of the system is the same for each frequency,
as indicated by a zero reading on the output meter. This adjust-
ment makes the over-all system response flat within the frequency
limitations of the compensator circuit.

The amplifier shown between the bridge circuit and the
compensator in figure 3 is a conventional audio-amplifier designed
to give a midfrequency gain of approximately 10,000 and with a
frequency response uniform to within 3 decibels over a range from 5
to 10,000 cycles per second. Figure 4 shows the typical wave forms
that exist at the amplifier output terminals and at the compensator
output terminals when the wire is simultaneously subjected to 100
and 500 cycles per second signals of equal amplitudes. The injected
frequencies are chosen at 100 and 500 cycles per second rather than
at two frequencies having a greater ratio because the essential
nonlinearity of the hot wire will produce intermodulation products
to which the tuned audio-amplifiers would respond.

THEORY OF COMPENSATOR CIRCUIT

The compensator circuit has been shown to be one of the
essential components in the constant-current dynamic hot-wire
system. The compensator circuit must have a frequency response
proportional to $1 + j\omega M$, the reciprocal of the right-hand side
of the amplitude reduction equation (8). The compensator circuit
developed for use with this equipment consists basically of a
series R-C circuit driven by a current source which is proportional
to signal amplitude and frequency.

If an alternating current is supplied to a series R-C circuit,
the voltage developed across the combination is

$$e = i\left(R + \frac{1}{j\omega C}\right)$$

$$= i\left(\frac{1 + j\omega M}{j\omega C}\right) \tag{10}$$

in which $M = RC$ = time constant in seconds when R is in ohms and C is in farads. The expression in parentheses is seen to be the reciprocal of the right-hand side of equation (8) except for the presence of the term $j\omega C$ in the denominator. This term may be canceled by taking the product of the response of the series R-C circuit and the response of a circuit which is proportional to $j\omega C$. The product of two such circuits may be obtained electronically by feeding the output of one circuit into the input of the second. The voltage output of such a combination is, then, the product of the responses of the individual circuits. In the actual compensator circuit the current i (equation (10)) includes the amplitude response of the wire as well as the frequency proportional factor which cancels $j\omega C$ in the denominator of the parenthetical expression. The numerator of this parenthetical expression compensates for the amplitude reduction factor expressed by equation (8).

APPARATUS

The Frequency Compensator

The compensator circuit used is shown in figure 5. The basic compensator circuit which determines the time constant is in the plate circuit of the third amplifier stage. This circuit consists of a fixed condenser C_M in series with a variable resistor R_M. The current to this circuit is supplied through a large series resistor R_s. This resistor is so chosen that the maximum impedance of the compensating R-C circuit is negligibly small by comparison.

The current of equation (10) is the current through the combination of R_M and C_M in the plate circuit of the third stage and is proportional to the signal amplitude and frequency. The combination of R_M and C_M has an impedance given by the equation

$$Z_M = \frac{1 + j\omega R_M C_M}{j\omega C_M} \tag{11}$$

In order to make the current through the combination of R_M and C_M relatively independent of the value of Z_M, a resistor R_s having an ohmic value much greater than the maximum value of Z_M through the desired frequency range (10 to 1000 cps) is placed in series with the combination.

The response proportional to frequency which is required to supply the basic compensator circuit R_M-C_M (to cancel the $j\omega C$-term in the denominator of equation (10)) is provided by the first stage. If the reactance of the coupling condenser C_c between the first two stages is made large compared with the resistance of the grid leak R_g to which it couples, throughout the desired frequency range the voltage across R_g is essentially proportional to $j\omega C$. Obviously this voltage cannot be exactly proportional to $j\omega C$ because of the resistive component of the coupling-circuit impedance. The component values shown introduce an amplitude error of less than 1 percent and a phase error of approximately 3° at the extreme condition (1000 cps).

The second stage of amplification serves to overcome the severe attenuation occurring in the first-stage coupling network; the signal must be maintained at a comparatively high level to minimize shot effect and microphonic noise generated in the tubes.

The Dynamic Calibrator

The dynamic-signal-injection equipment shown in figure 6 consists of two oscillators (100 and 500 cps), the outputs of which are mixed and then supplied to a push-pull power amplifier. The oscillators used are of the phase-shift type. This type was selected because of the good wave forms obtainable at the low frequencies employed. The mixer is of a conventional type. The output of the mixer is supplied to a "floating paraphase" phase inverter (reference 5). This inverter in turn supplies a conventional power amplifier. Voltage feedback from the power amplifier to the phase inverter is utilized to stabilize the gain of the system. The output transformer chosen has a rating considerably greater than the power actually consumed for reasons explained in the discussion of the bridge circuit.

Compensation Detector

In order to permit the comparison of the response of the wire to the two injected signal frequency components when the wire is subjected to fluctuating flow conditions in a wind tunnel, it has been necessary to develop individual detector amplifiers sharply tuned to the calibrating signal frequencies. These tuned amplifiers shown in figure 7 are used for detecting the injected signal frequencies in the compensator output. Extremely narrow bandwidths may be obtained in these amplifiers by making use of a parallel-T null network in the feed-back loop to produce a peak amplification

at the network null frequency (reference 6). The gain is stabilized
by the use of an additional feed-back loop to the input cathode.
The null-network output is fed back to the input stage on one grid
of the input dual triode, which is electrically equivalent to feeding
a part of this voltage to the cathode of the same tube. The circuit
used has the advantage of allowing the voltage feedback to be
introduced at a high impedance level in the input circuit. A pair
of infinite impedance detectors are used in the tuned-amplifier
outputs. The indicator meter is connected between the two outputs
so that differences in response to the two injected frequencies
are indicated by the meter.

The operation of this equipment is as follows: the two
calibrating frequencies, 100 and 500 cycles per second, are injected
simultaneously into the hot-wire bridge with the wire mounted in
the tunnel and the tunnel operating at the conditions under which
data observations are to be made. The variable resistor R_M in
the frequency compensator circuit is then adjusted until the meter
reading the difference between the two injected-frequency components
present in the output reads zero. The frequency response of the
system is then uniform throughout the design range (10 to 1000 cps)
and will remain so as long as the tunnel operating conditions are
not changed.

Instances may conceivably occur in which the tunnel conditions
will be continuously changing during a series of test observations.
A continuously variable self-balancing frequency compensation may
be effected by feeding the voltage that would normally be applied
to the compensation indicator meter into the input of an amplifer
which drives a motor to turn the shaft of the rheostat R_M. This
continuous adjustment would take place up to the instant of data
observations. Several such self-balancing systems are available
commercially and the addition of this feature would entail only a
slight circuit modification.

Experimental Verification of the Dynamic System

Experimental verification of the dynamic system is demonstrated
in figures 8 and 9. A typical experimental frequency-response curve
for the compensator circuit for a time-constant setting corresponding
to high-speed tunnel operating conditions (Mach number = 0.75;
0.0005-inch-diameter tungsten wire; time constant = 2×10^{-3} sec)
is shown in figure 8. The setting of the compensator for this curve
was determined with the system and the techniques described previously
herein. Figure 9 shows the result of graphical combination of the
experimental response curves of the wire and the compensator having

the same time constant $(2 \times 10^{-3}$ sec). This combined frequency-response curve shows the response of the system to be flat within approximately 10 percent throughout the frequency range for which measurements were made.

CONCLUDING REMARKS

A re-examination of the hot-wire theory has shown that the hot-wire anemometer is applicable to dynamic measurements of small fluctuations under any flow conditions which permit a static calibration to be made.

The equipment described permits a rapid empirical compensation of a hot wire under actual operating conditions.

The frequency-response relationships based upon classical hot-wire theory are also applicable to compressible-flow conditions if the factors involved are properly evaluated.

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        National Advisory Committee for Aeronautics
                Langley Field, Va., April 18, 1947

REFERENCES

1. Dryden, H. L., and Kuethe, A. M.: The Measurement of Fluctuations
      of Air Speed by the Hot-Wire Anemometer. NACA Rep. No. 320,
      1929.

2. Mock, W. C., Jr., and Dryden, H. L.: Improved Apparatus for the
      Measurement of Fluctuations of Air Speed in Turbulent Flow.
      NACA Rep. No. 448, 1932.

3. King, Louis Vessot: On the Convection of Heat from Small Cylinders
      in a Stream of Fluid: Determination of the Convection Constants
      of Small Platinum Wires with Applications to Hot-Wire Anemometry.
      Phil. Trans. Roy. Soc. (London), ser. A, vol. 214, Nov. 12, 1914,
      pp. 373-432.

4. Ziegler, M.: The Application of the Hot-Wire Anemometer for the
      Investigation of the Turbulence of an Airstream. Koninklijke
      Akad. Wetenschappen Amsterdam. Reprinted from Proc.,
      Vol. XXXIII, no. 7, 1930, pp. 723-736.

5. Smith, F. Langford: Radiotron Designer's Handbook. Third ed.,
      The Wireless Press (Sydney, Australia), 1941, p. 12. (Reproduced
      in U.S.A. by RCA Manufacturing Co., Inc., Harrison, N.J.,
      Nov. 1941.)

6. Hastings, A. E.: Analysis of a Resistance-Capacitance Parallel-T
      Network and Applications. Proc. I.R.E. and Waves and Electrons,
      vol. 34, no. 3, March 1946, pp. 126P-129P.
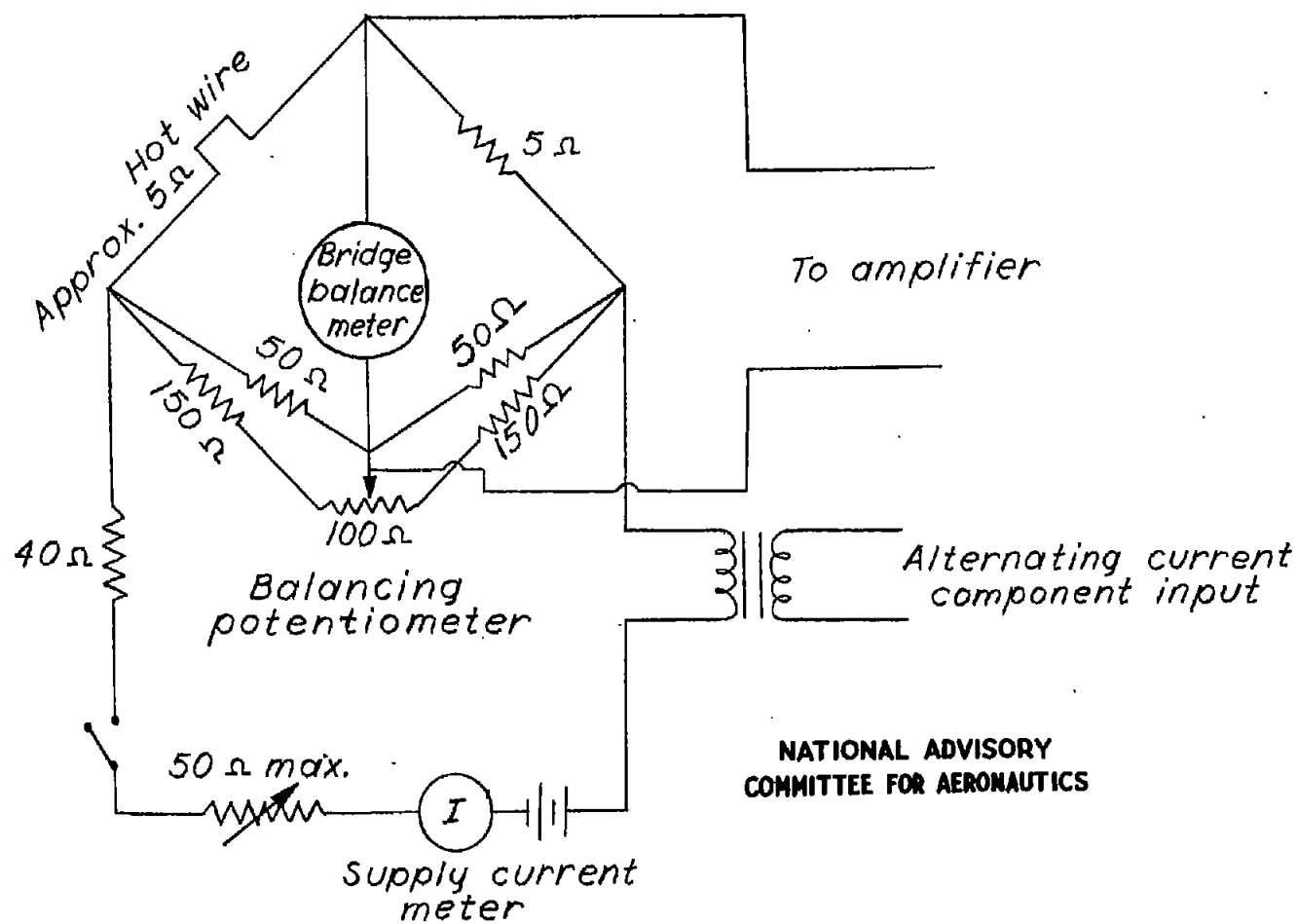
Figure 1.- Hot-wire bridge circuit for use with dynamic-calibration equipment.

Fig. 1

Fig. 2
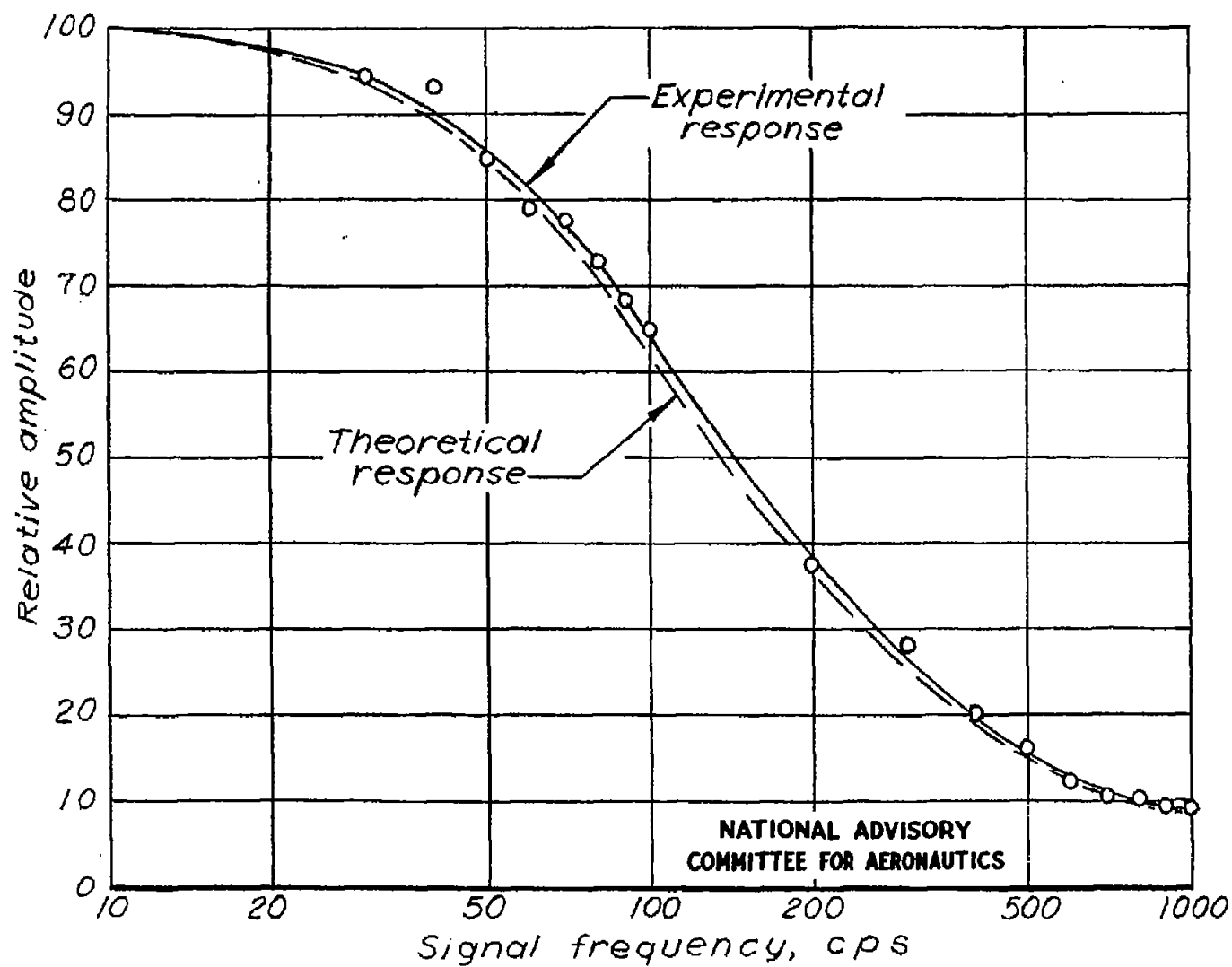
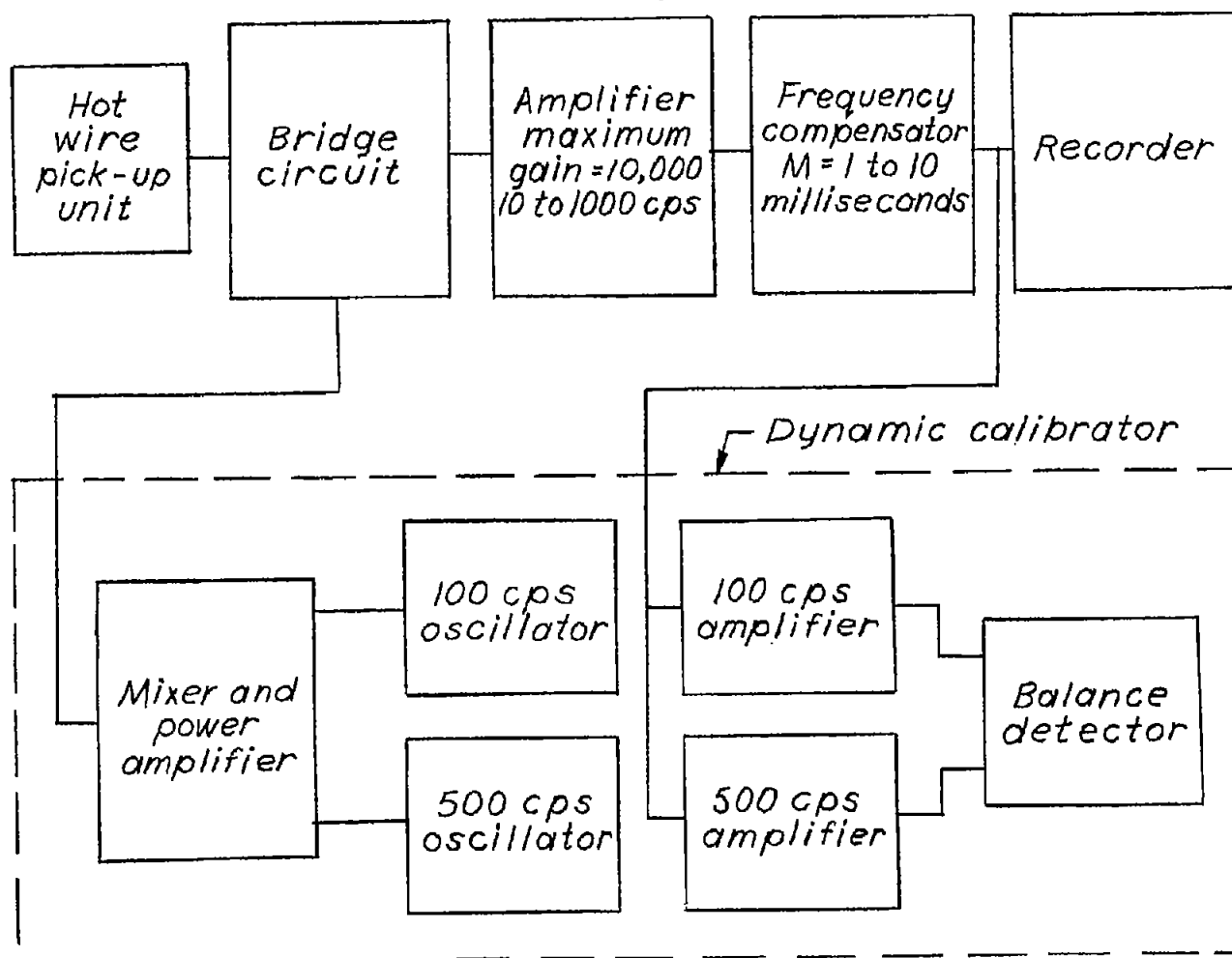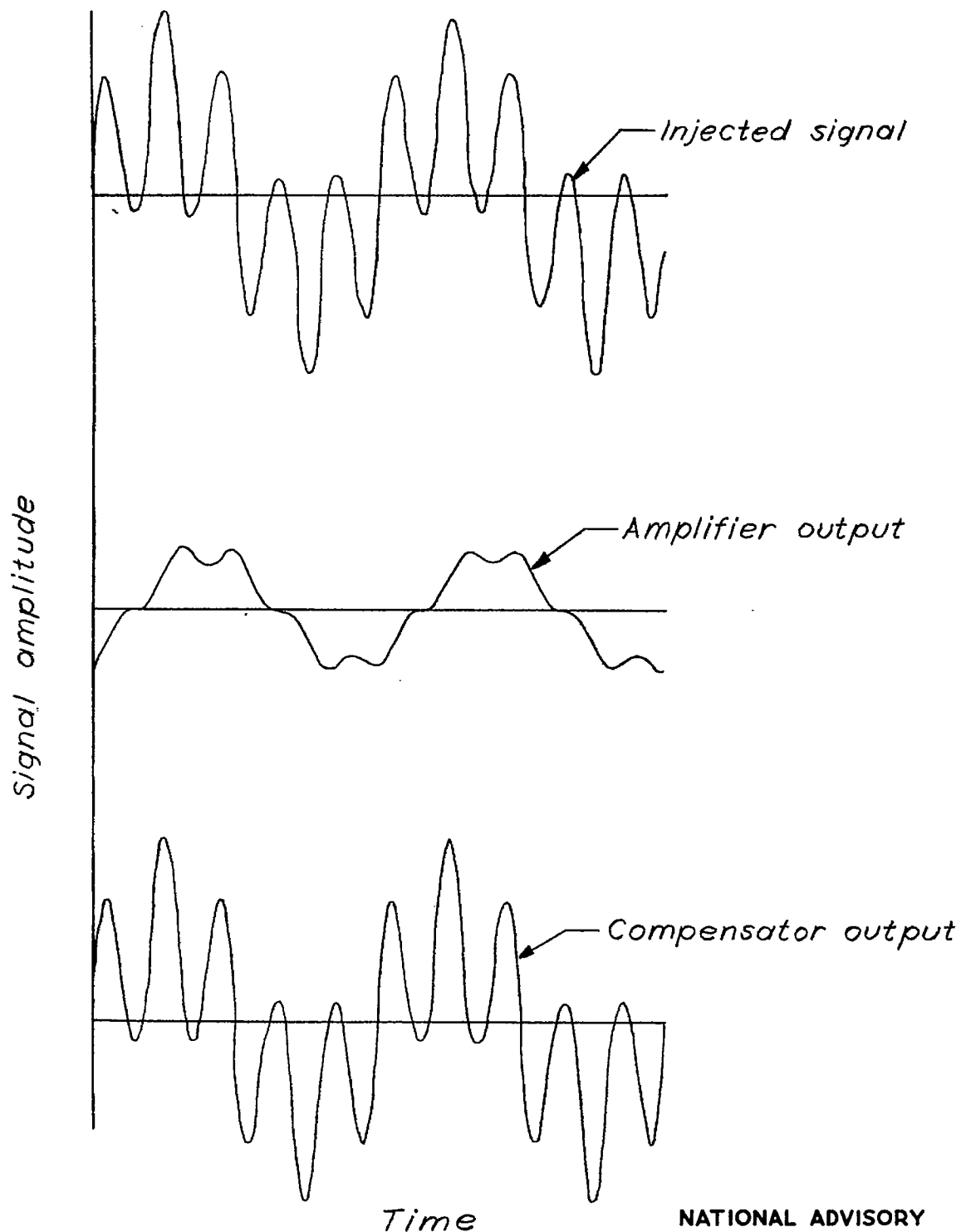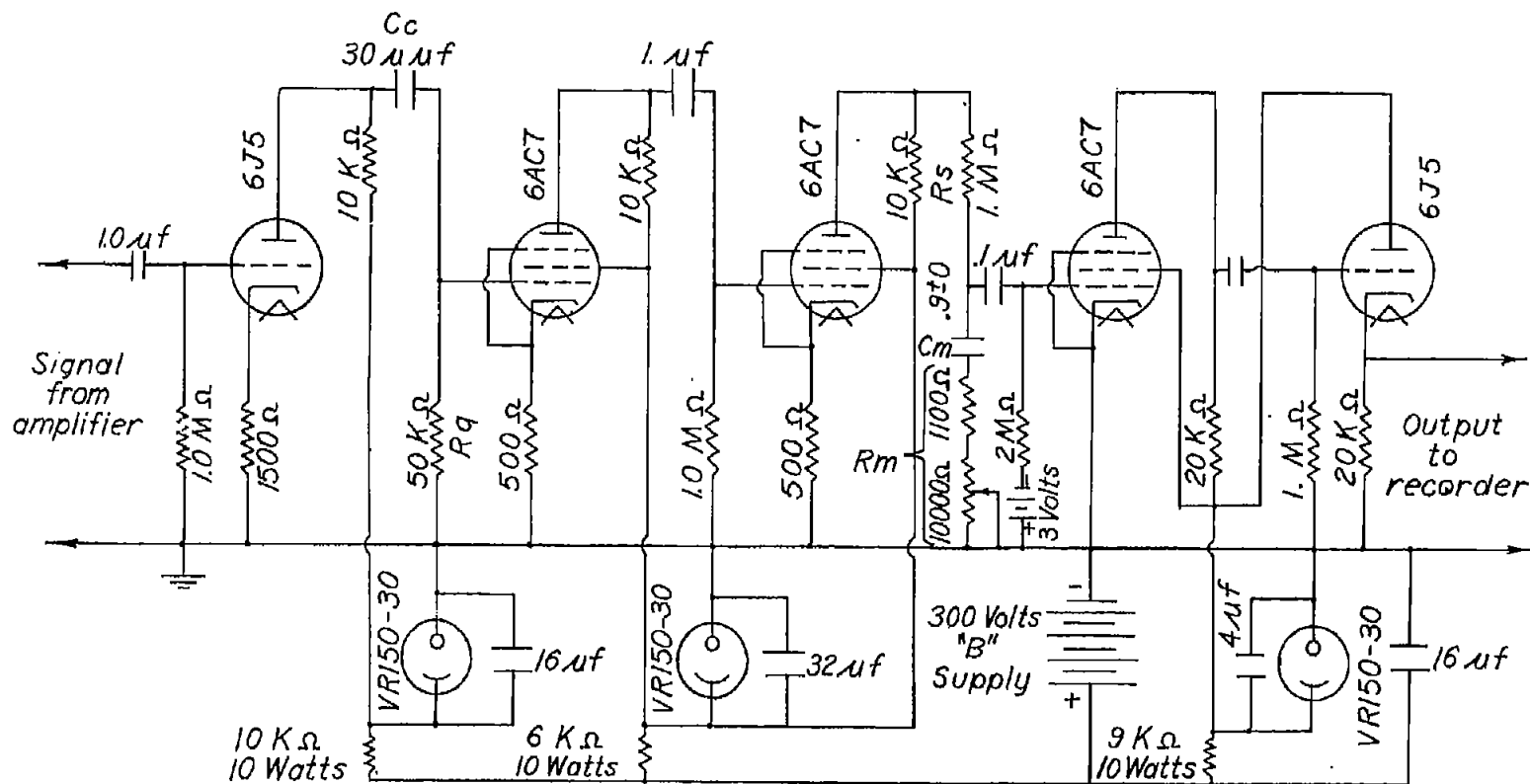Figure 2.-   Experimental frequency response of the hot wire.

Fig. 3

Figure 3.- Block diagram of dynamic hot-wire system.

Fig. 4

Figure 4.- Action of the compensator circuit.

Figure 5.- Compensator-circuit diagram.

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Fig. 5

Fig. 6

Figure 6.- Dynamic-signal-injector equipment.

Fig. 7
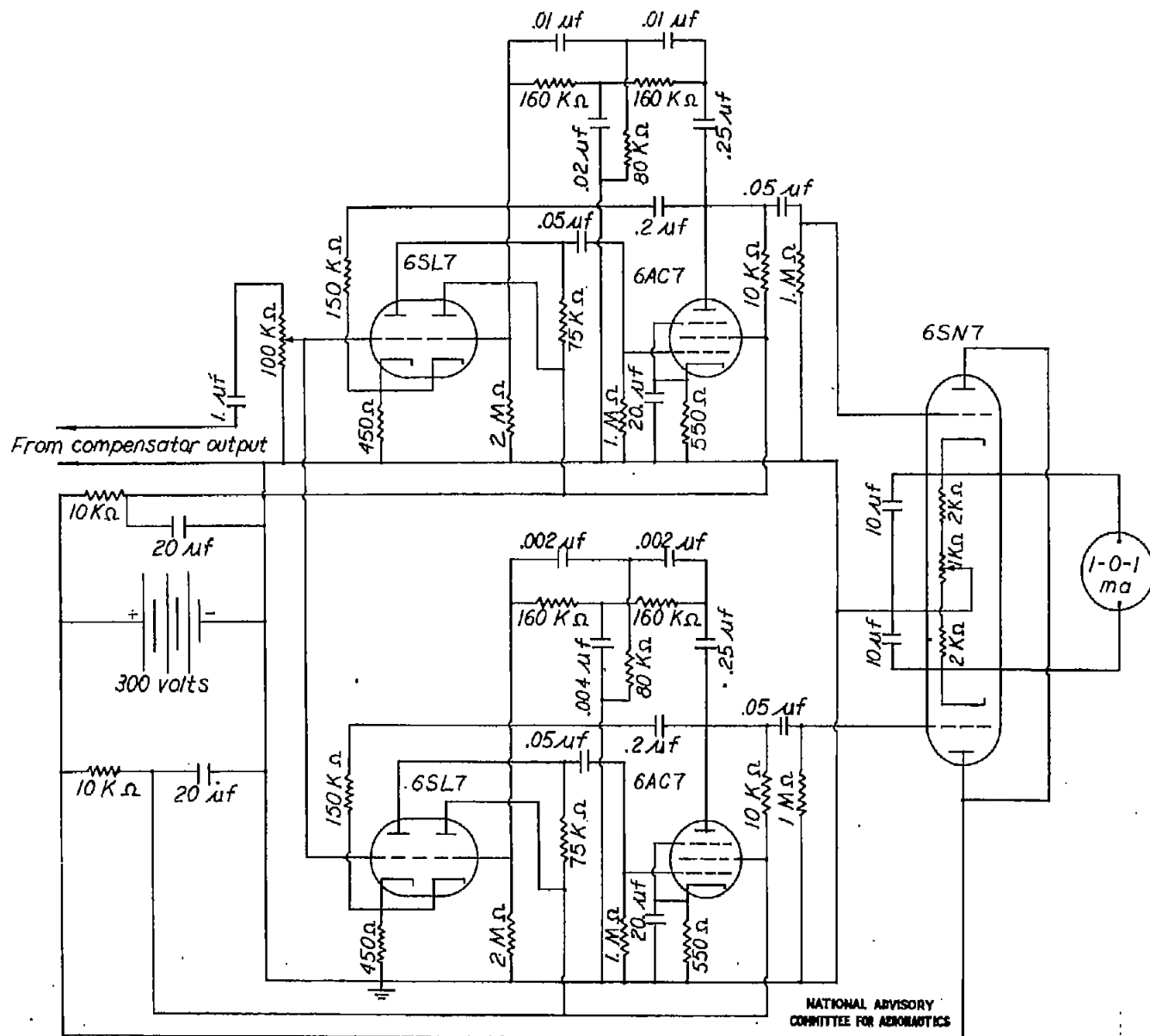
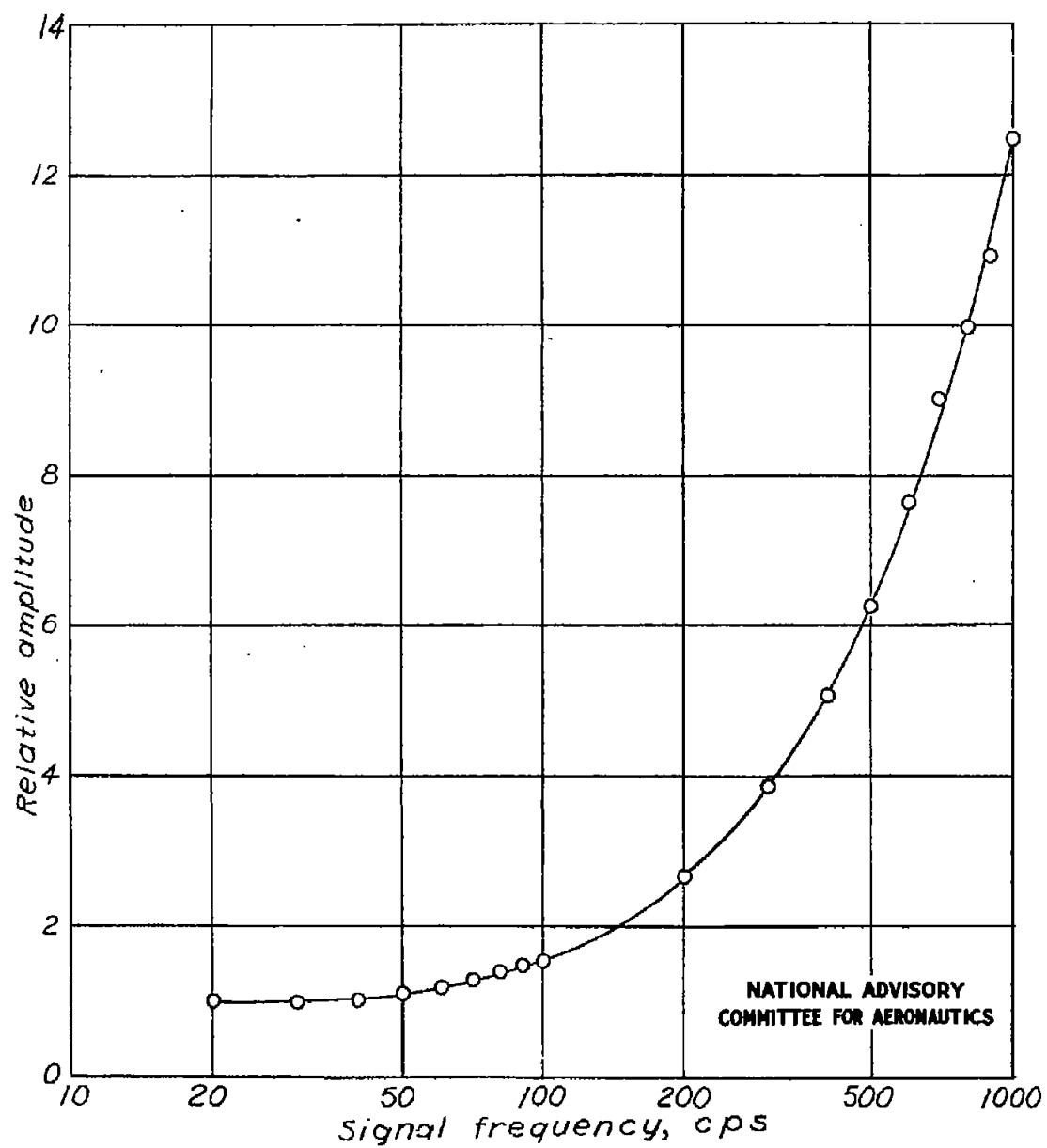Figure 7.- Compensation detector circuit.

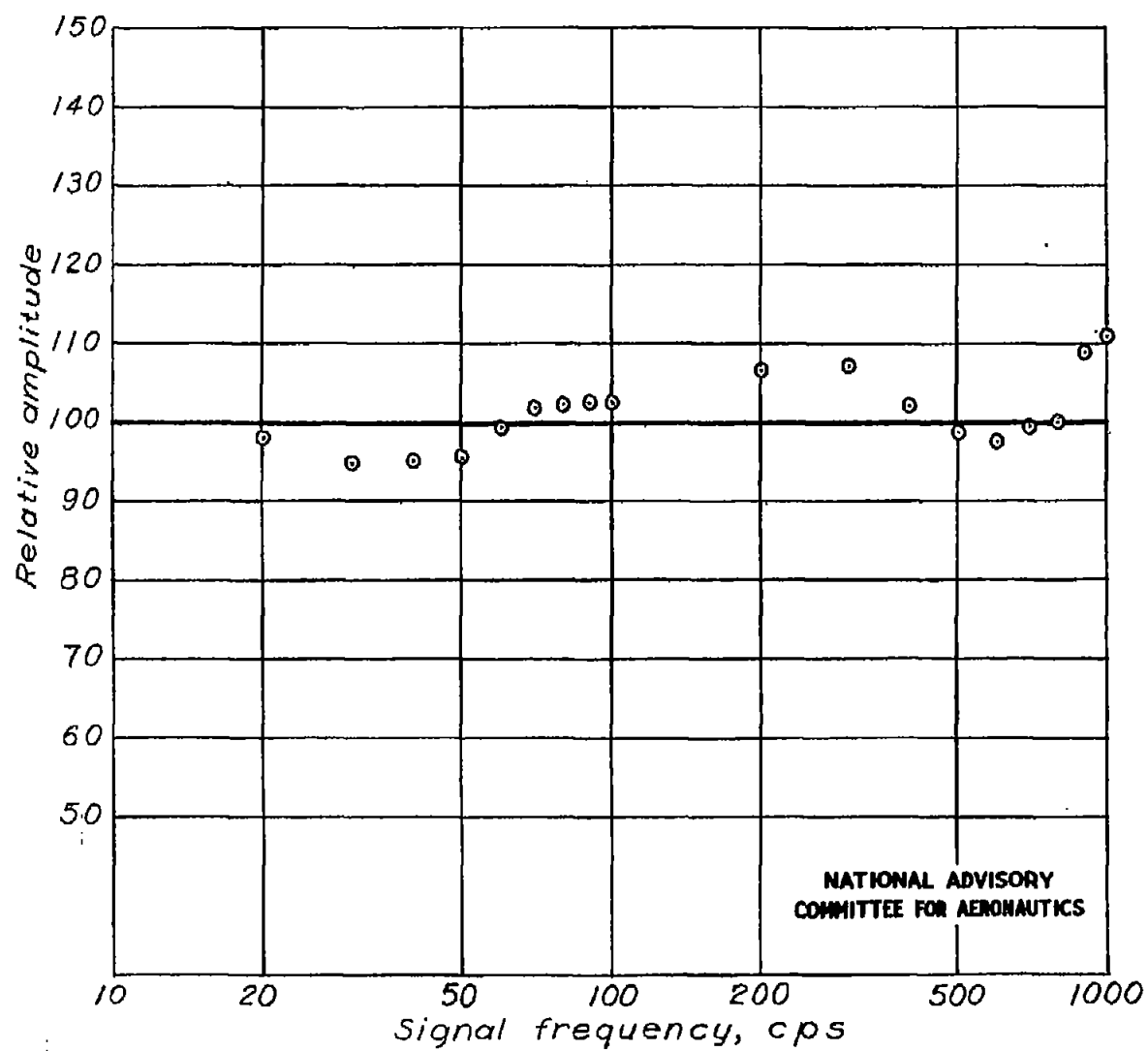Fig. 8

Figure 8.- Experimental frequency response of compensator circuit.

Figure 9.- Graphical combined response of hot-wire system.

Fig. 9